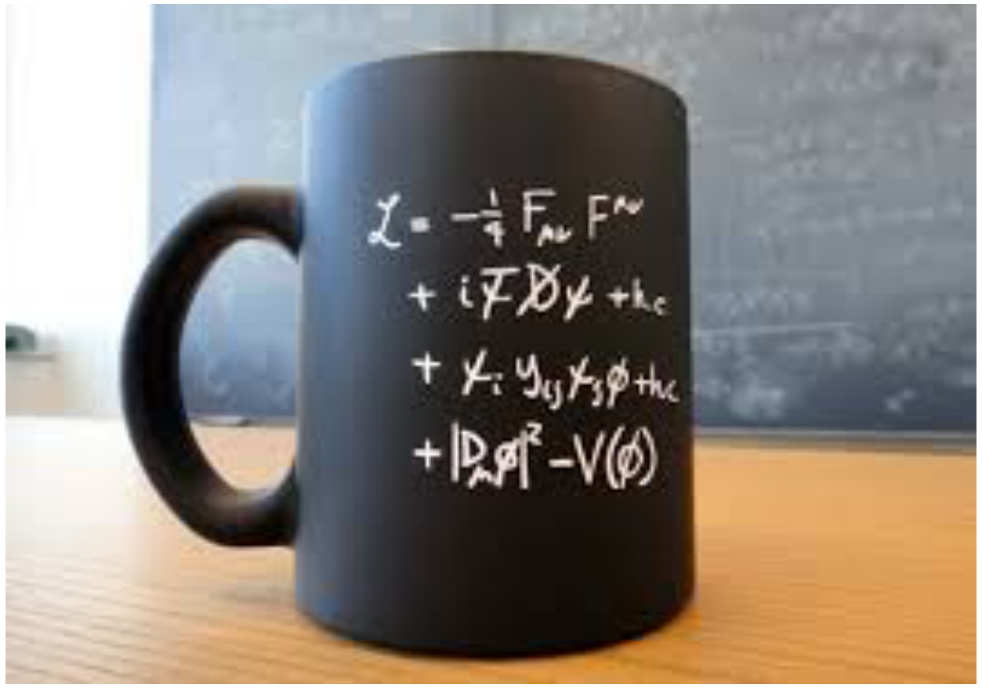
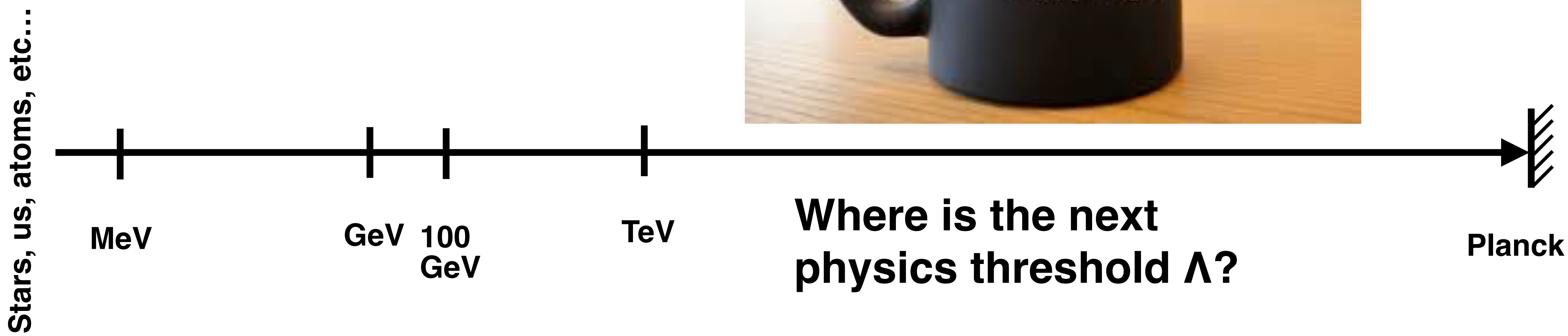
The Neutrino Portal: sterile neutrinos, cosmology and other signatures

Luca Vecchi
(EPFL)

L.N. Frascati 22/5/2018

Very special time in Particle Physics…



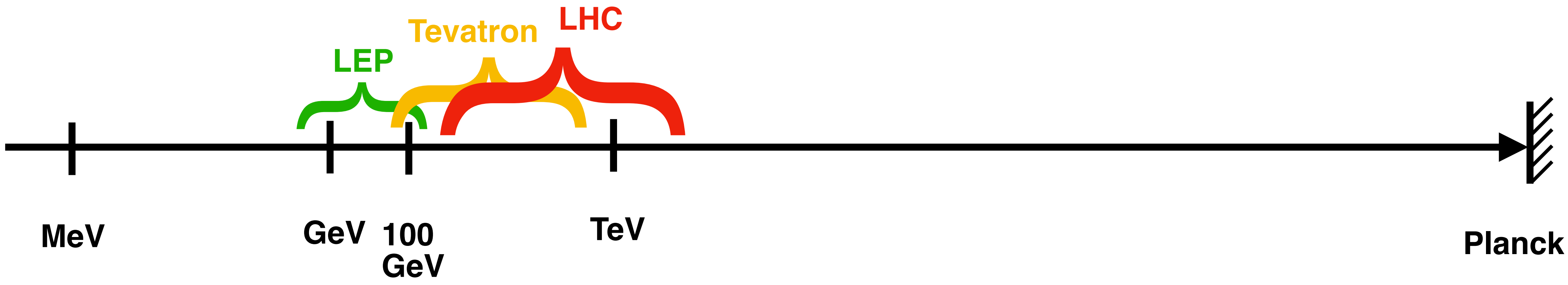


Where is the next physics threshold Λ?

…The Standard Model is the first particle model that is conceptually and phenomenologically consistent up to the ultimate scale of Particle Physics (Planck)!!!

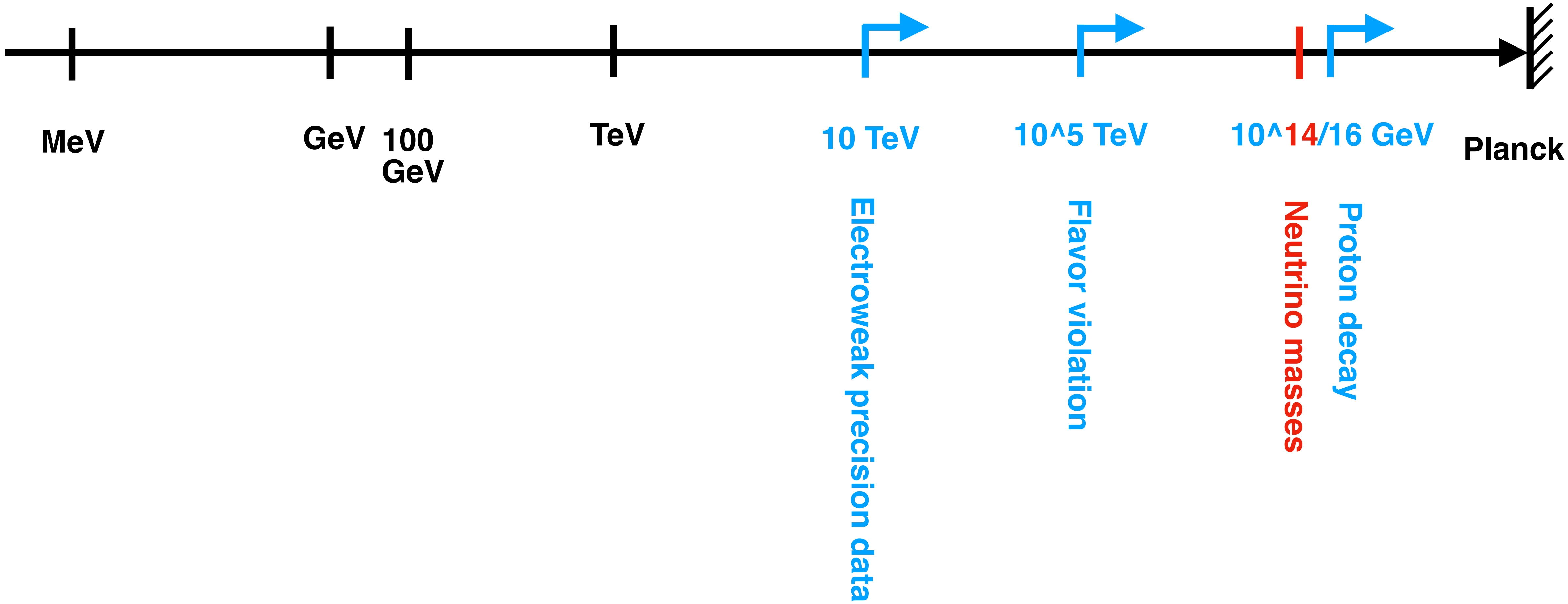
What do experiments say?

Direct probes:



What do experiments say?

Indirect probes:



What to do NOW?

- **Keep pushing** (we know something is missing: dark matter, baryogenesis, etc.)
  Precision measurements

- **Study the particles we understand the least**
  Higgs boson
  — Only know up to 10%!
  — New physics? Expected from the hierarchy problem
  Neutrinos
  — Majorana or Dirac?
  — Absolute mass scale?
  — CP phase?
  — New physics?

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  — Absolute mass scale?
  — CP phase?
  — New physics?

WHY:
(1) Only guaranteed (in principle) **access to new physics**…
(2) Three main ways dark sectors can talk to us → **neutrino portal is one**.
(3) A big Experimental effort → **How can they surprise us?!**
(4) Dark energy density of order the neutrino mass scale → **any fundamental reason?**

Outline

- **The Neutrino Portal**
  - Q: What new physics can be discovered in neutrino experiments?
  - Light dark sectors and cosmology
- **Light & Weakly-Coupled Dark Sectors**
  - A: Sterile neutrinos directly and/or as mediators of exotic interactions
    1) Dark backgrounds
    2) Dark backgrounds or neutrino masses?
- **Conclusions**

Light Dark Sectors Coupled to Neutrinos

The three “portals” to Standard Model-singlet sectors…

Severely constrained:
involves charged particles
(dark Z’, dark matter dipoles, etc.)

Neutrino portal:

$$O_F = N,\ \phi\nu_s,\ \sigma^{\mu\nu}\psi^a F^a_{\mu\nu},\ \psi\psi\psi,\ \cdots$$

$$\delta\mathcal{L} = O_T^{\mu\nu} B_{\mu\nu} + O_S |H|^2 + O_F H L + \cdots$$

Very weakly constrained:
involves a poorly-known particle

All above choices interpolate sterile neutrinos

$$\delta\mathcal{L} \supset O_F H L \longrightarrow \delta\mathcal{L} \supset y_a N H L + (\text{dynamics for } N)$$

Heavy mass limit:

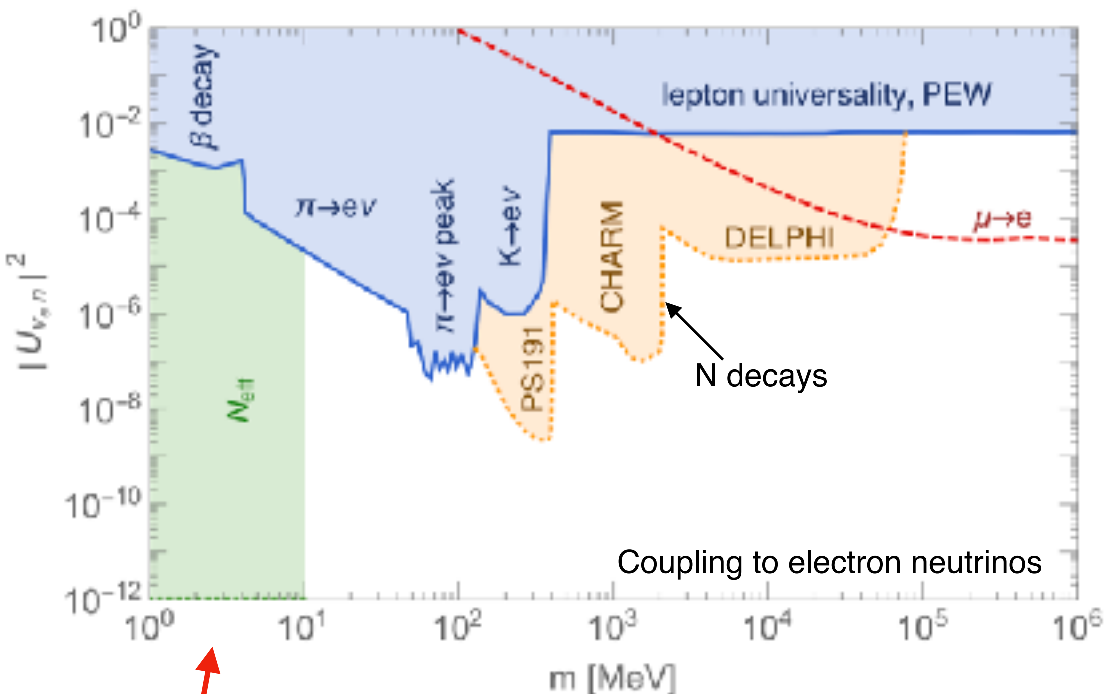
$$c^{(5)}_{\alpha\beta}(HL_\alpha)(HL_\beta) + c^{(6)}_{\alpha\beta}(HL_\alpha)^\dagger \bar{\sigma}^\mu i\partial_\mu (HL_\beta) + \cdots$$

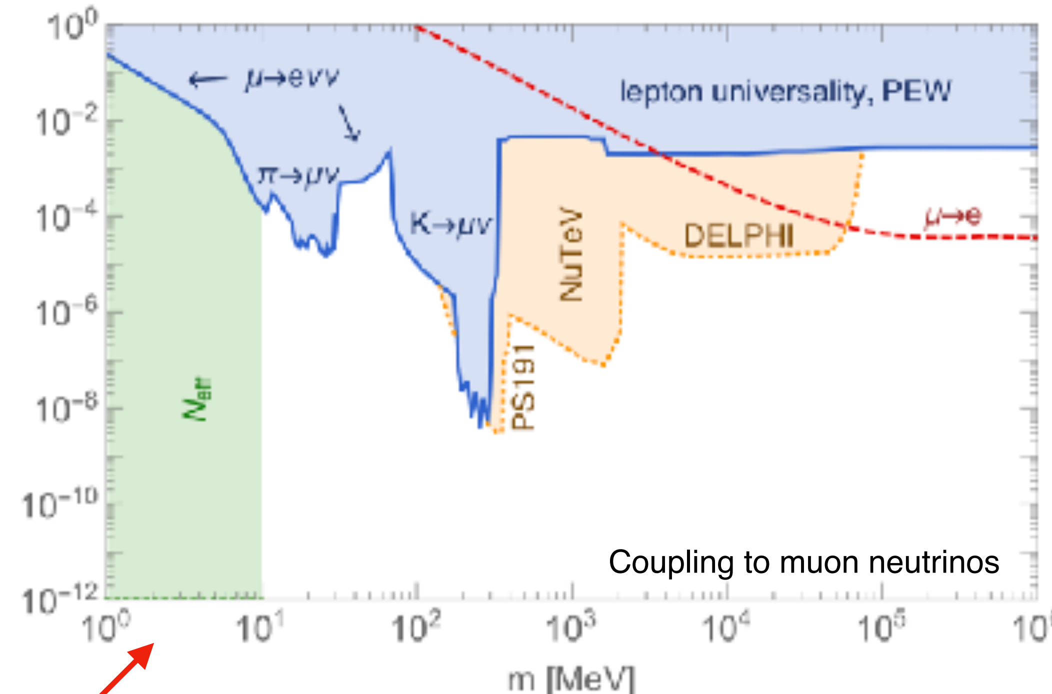
$$\downarrow \qquad\qquad\qquad \downarrow$$

$$m_\nu \qquad\qquad\qquad U_{\rm PMNS}$$

Intermediate mass limit:

From Schmaltz-Weiner (2017)



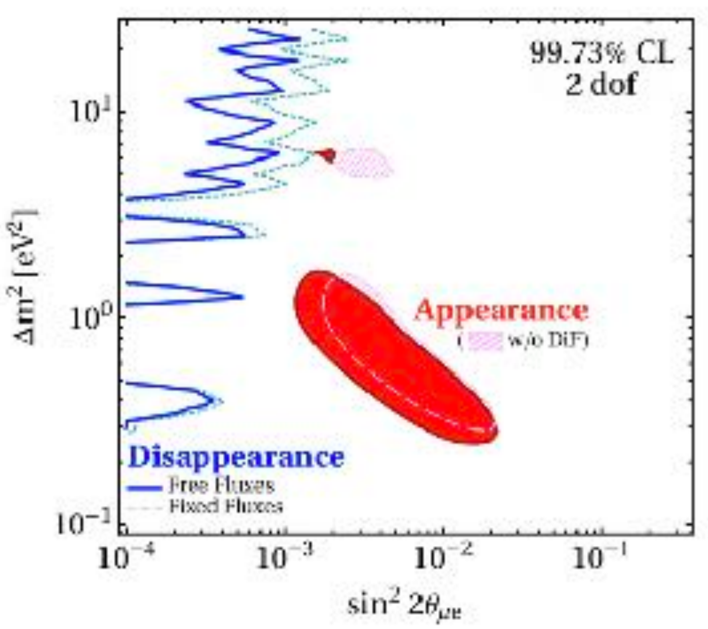


Q: Neutrino experiments (mixing)?!

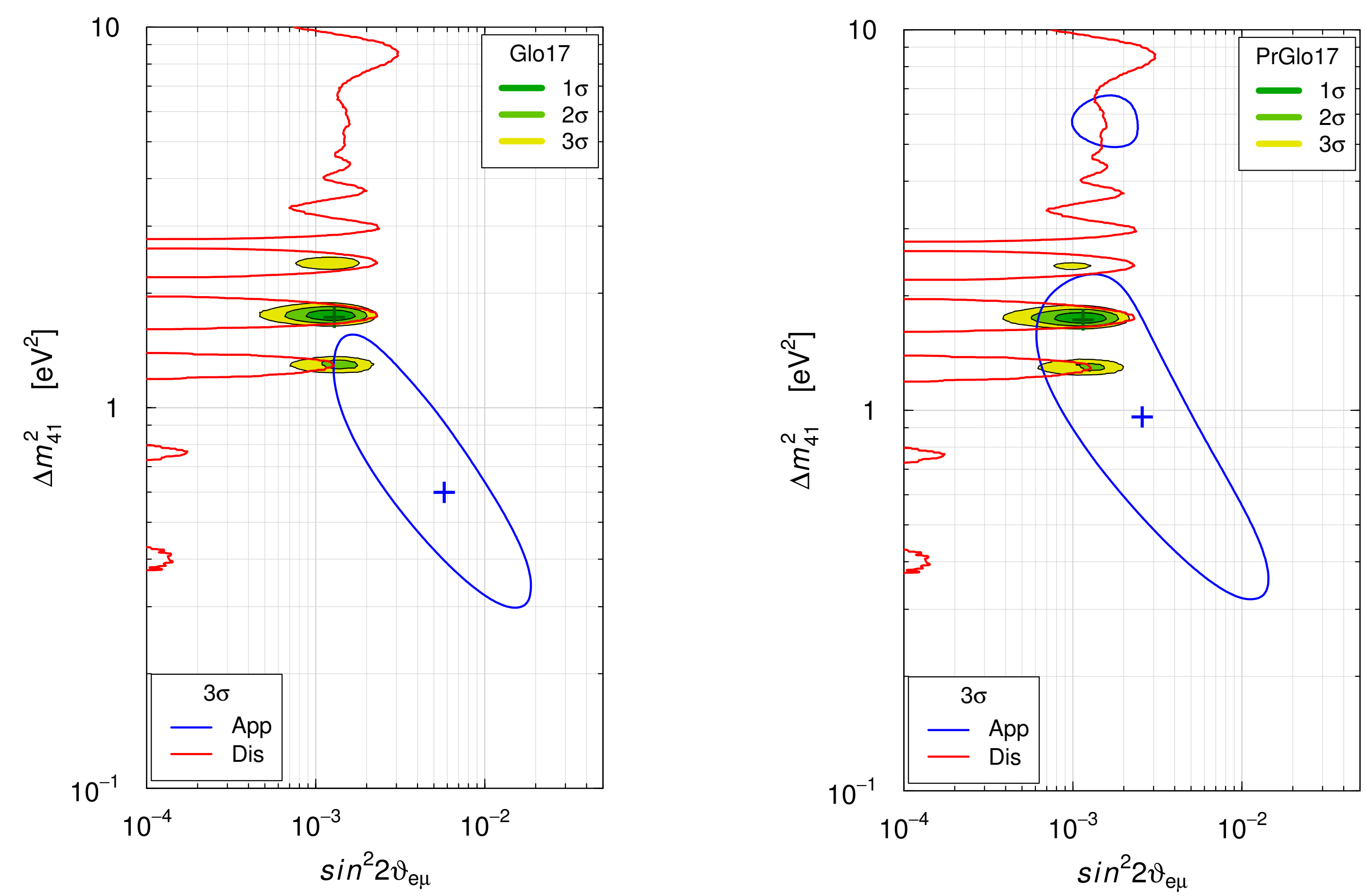
We need light sectors and we have to deal with cosmology

Light steriles are not obviously excluded by neutrino experiments…

Maltoni et al. (2018)



Giunti et al. (2017)



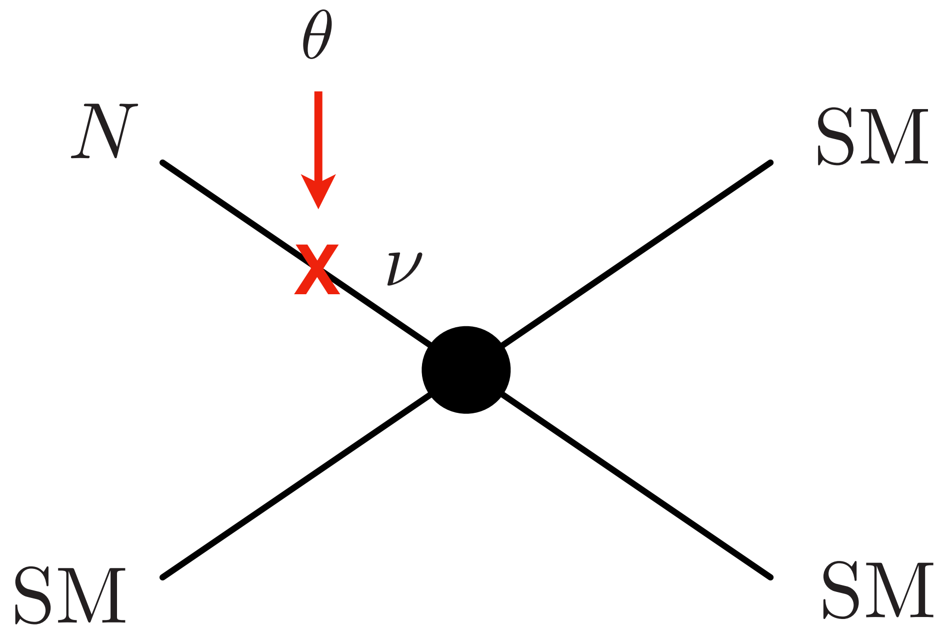
3+1 model $\sin^2 2\theta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$

Light Dark Sectors And Cosmology

The simplest option: **“free” N**

$$\mathcal{L} \supset y_a NHL + \frac{m_N}{2} NN + \text{hc}$$

mixing: $\theta \sim \min\left(\frac{y_a v}{m_N}, \frac{m_N}{y_a v}\right)$



$$\Gamma \sim G_F^2 T^5 \theta^2 \gg H$$

For θ>10^-7 and light N
the Dark Sector thermalizes:
Radiation at BBN & CMB!

Planck (2015)
$$\begin{cases} \Delta N_{\text{eff,BBN}} = 0.66 \pm 0.45 \\ \Delta N_{\text{eff,CMB}} = 0.10 \pm 0.23 \\ \sum_{\text{rel}} m_\nu < 0.3 \text{ eV} \end{cases}$$

How general?

$$\delta\mathcal{L} \supset y_a NHL + (\text{dynamics for } N)$$

↑

This may be non-trivial!

1) Suppression of production via large lepton asymmetry or large couplings to the plasma:
Foot Volkas (1995), Chu Cirelli (2006), Krauss et al. (2010), Hannestad et al. (2012), Mirizzi et al. (2012), Kopp et al. (2016)…

2) Dilution of the sterile population:
Gelmini et al. (2004), Fuller et al. (2011), Ho Scherrer (2012), …

3) Forbid oscillations via chiral symmetry:
LV (2016)

Another option: A chiral sterile
via the Dirac neutrino portal…

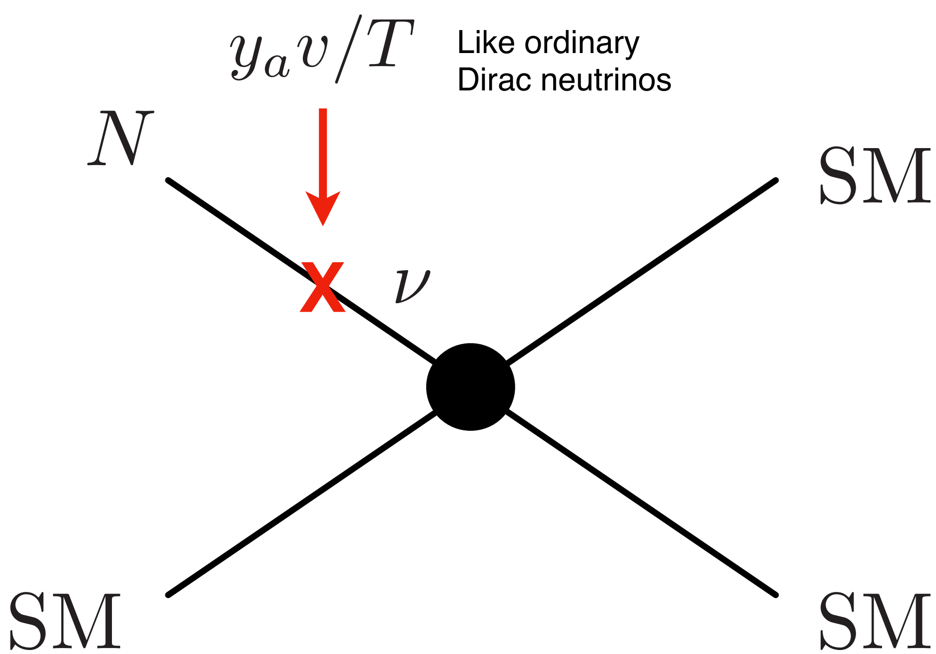
light sterile sector

$$\mathcal{L} \supset y_a N H L + y_s N \phi \nu_s + \mathrm{hc}$$

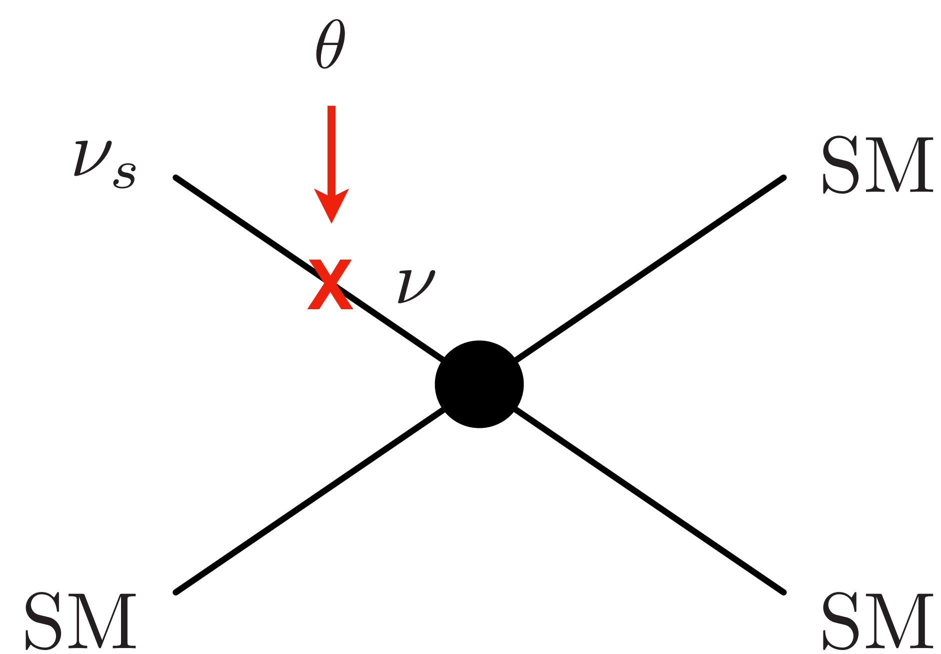
mixing: $\theta \sim \min\left(\frac{y\langle H\rangle}{y_s\langle\phi\rangle}, \frac{y_s\langle\phi\rangle}{y\langle H\rangle}\right)$ **KEY!**

SM interactions

$$\mathcal{L} \supset y_a N H L + y_s N \phi \nu_s + \text{hc}$$



<ϕ>=0

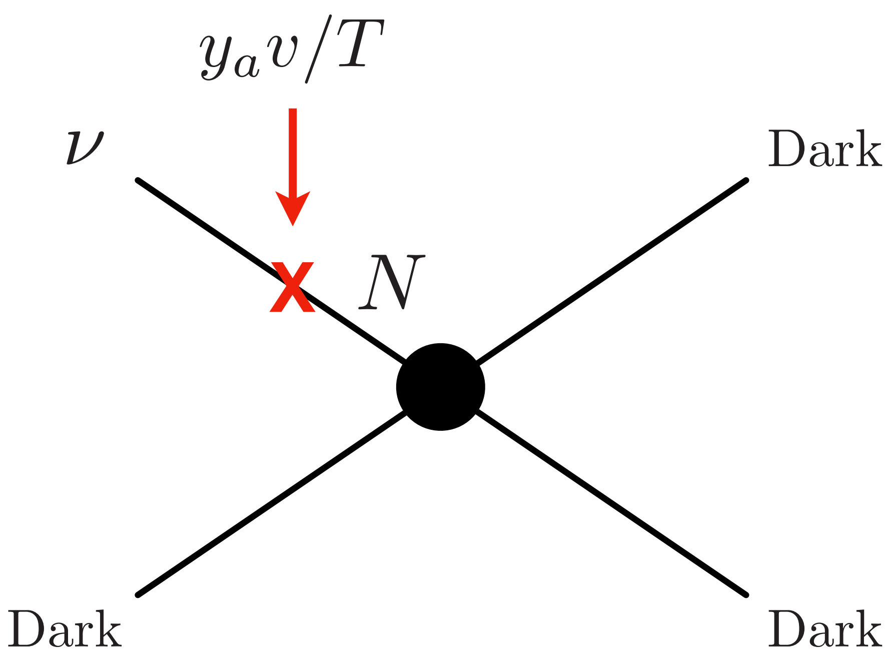


<ϕ>≠0

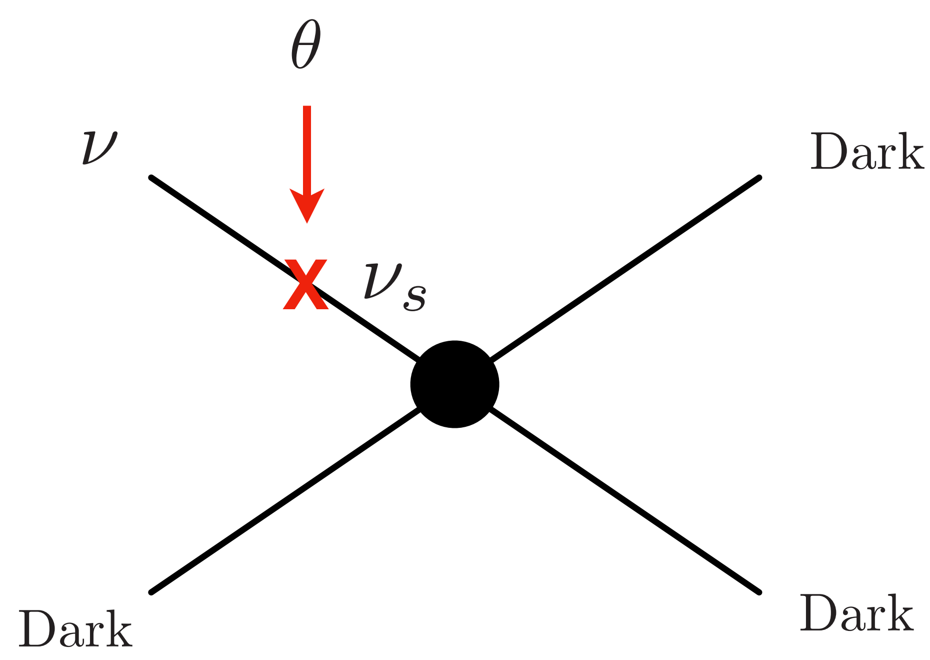
SM interactions are inefficient
If <ϕ>=0 before neutrino decoupling!!!

Dark interactions

$$\mathcal{L} \supset y_a N H L + y_s N \phi \nu_s + \text{hc}$$



<ϕ>=0

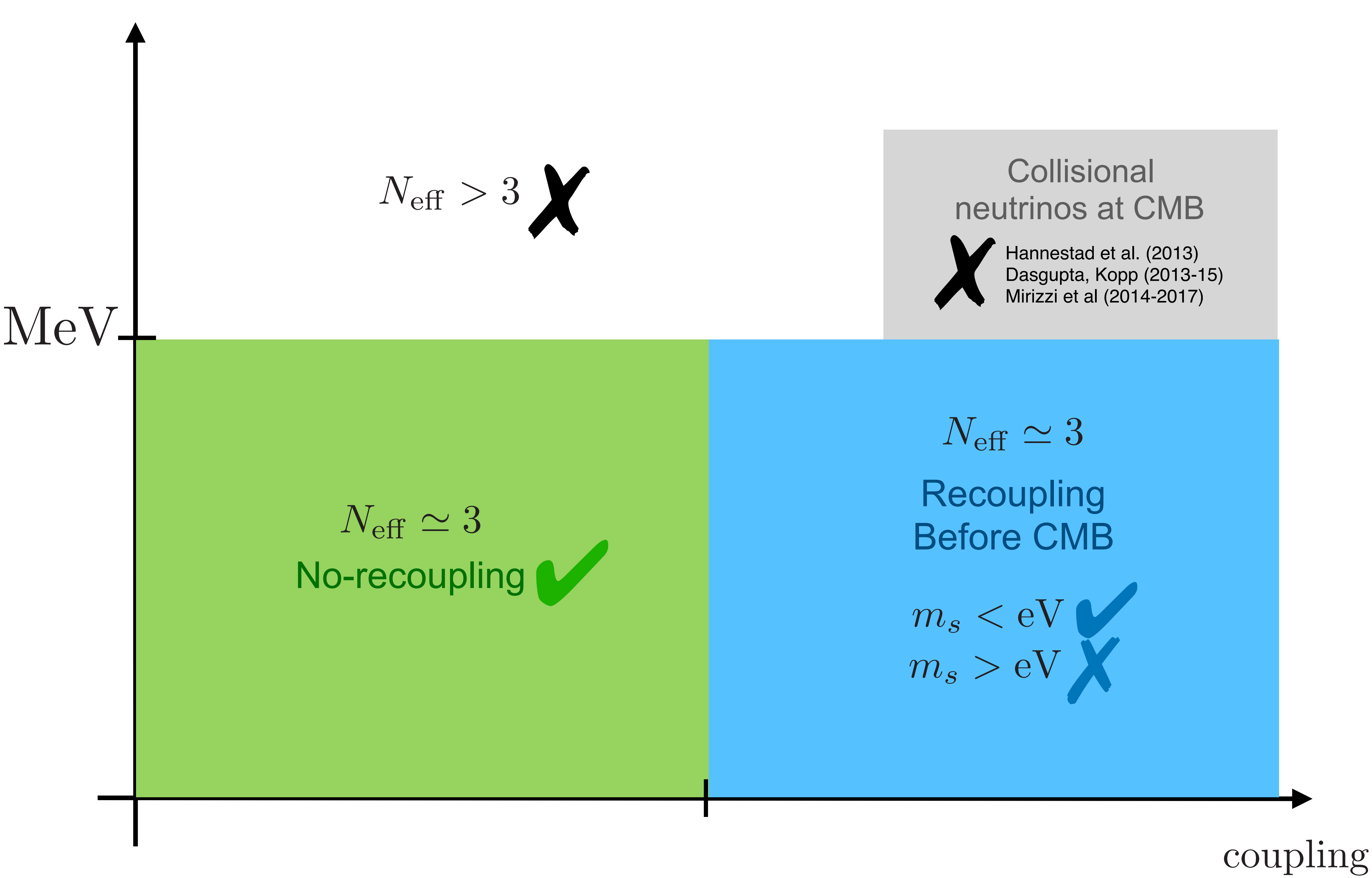


<ϕ>≠0

Depend on the Dark Sector's
— couplings
— masses
— primordial abundance
We do not know!

Qualitative typical picture…

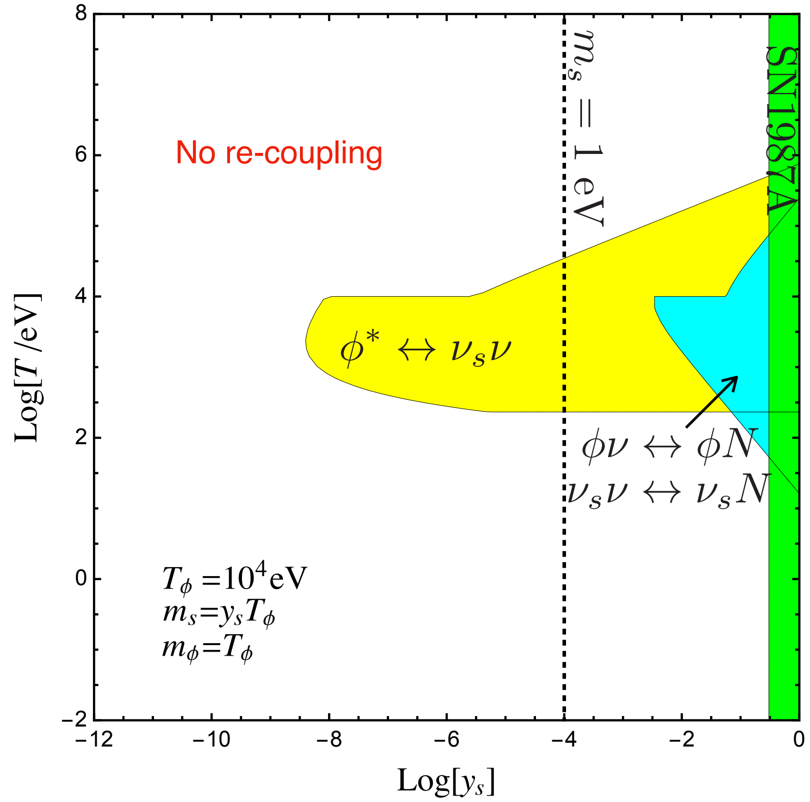
$$\mathcal{L} \supset y\ell H O + \cdots$$



A chiral sterile
via the Dirac neutrino portal:

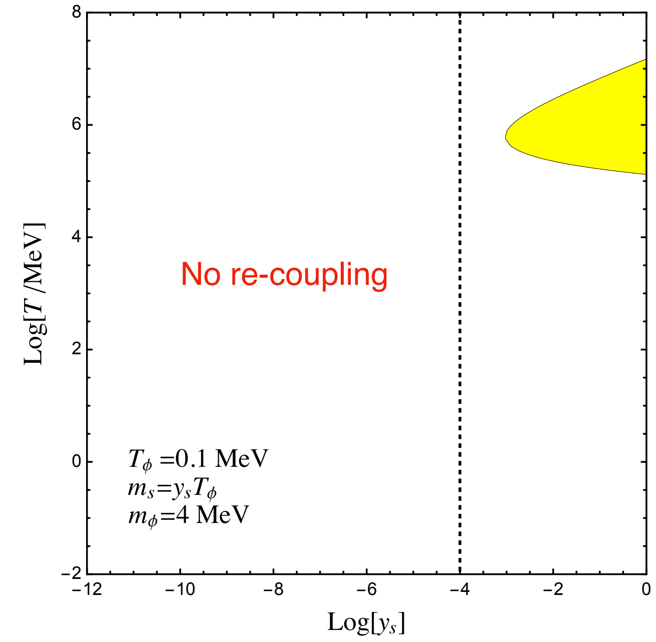
$$\mathcal{L} \supset y_a NHL + y_s N\phi\nu_s + \text{hc}$$

Option 1
Dark sector was in equilibrium earlier



$N_{\text{eff}} \simeq 3$

Option 2
First order transition at low T

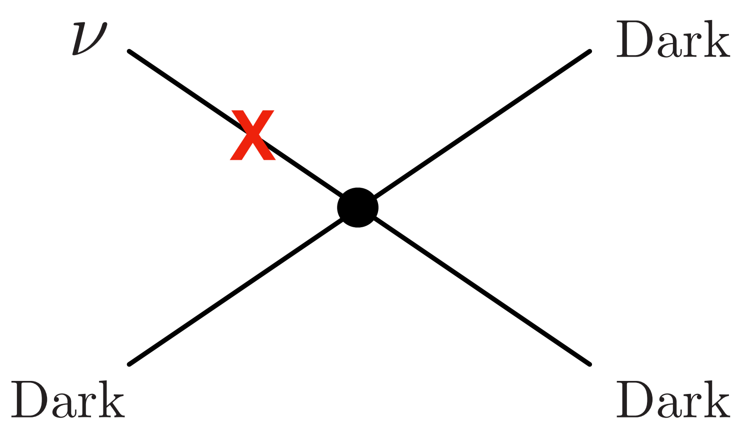


Option 3
Dark sector has a small primordial abundance
→ No re-coupling

Light Dark Sectors And Astrophysics

Neutrino propagation in the Cosmo?

SN1987A: mean free path (for E=10 MeV) larger than 50 kpc…
IceCube: mean free path (for E=PeV) larger than 50 Mpc…

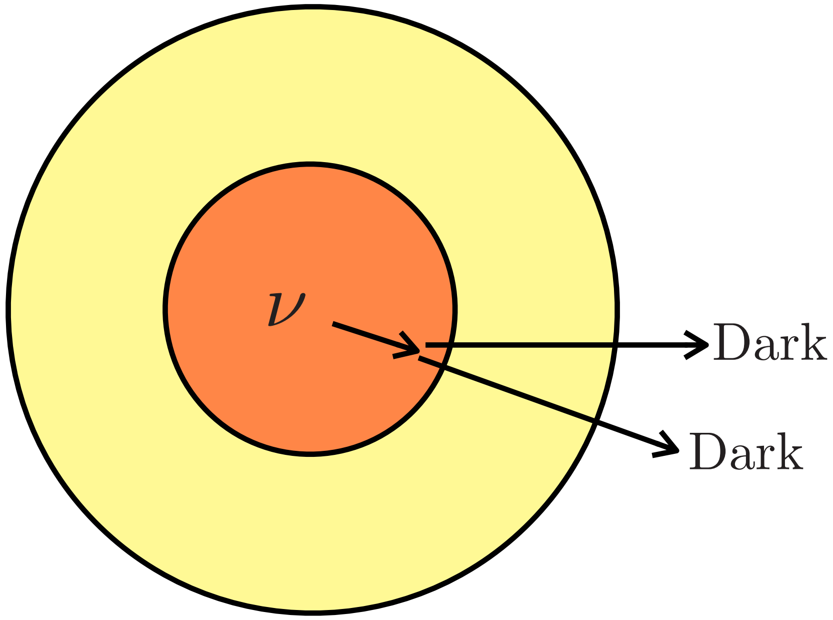


$$\frac{1}{\ell} \sim \frac{y_s^4}{4\pi s}\theta^2 n_{\rm dark} \implies y_s^2\theta < 10^{-6}$$

From SN1987A
Assuming thermal density
And massless particles

Worst case: there is a background of dark particles
(otherwise more powers of θ)

Weak-coupling → Star cooling (supernova)?



$$\propto y_s^2 \theta^2_{\rm matt} \sim y_s^2 \theta^2 \frac{\Delta m^2}{V_{\rm matt} E} \lll 1$$

No significant constraint…

1) Difference from standard steriles: here we can produce exotic states!

2) As opposed to QCD axion:

— produced by neutrino-rich stars

— need mixing, but θ is "matter-suppressed" at large densities

Topological defects

Produced at the Dark phase transition by the Kibble-Zurek mechanism

Temperature now

$$\rho_{\rm strings} \sim \frac{\langle\phi\rangle^2 \xi}{\xi^3}\left(\frac{T_0}{T_\phi}\right)^2 \ll \rho_{\rm CC}$$

Correlation length at production

Temperature at production

— correlation length estimated using Zurek results (see also Murayama et al.)

— to be conservative: no dilution due to string dynamics

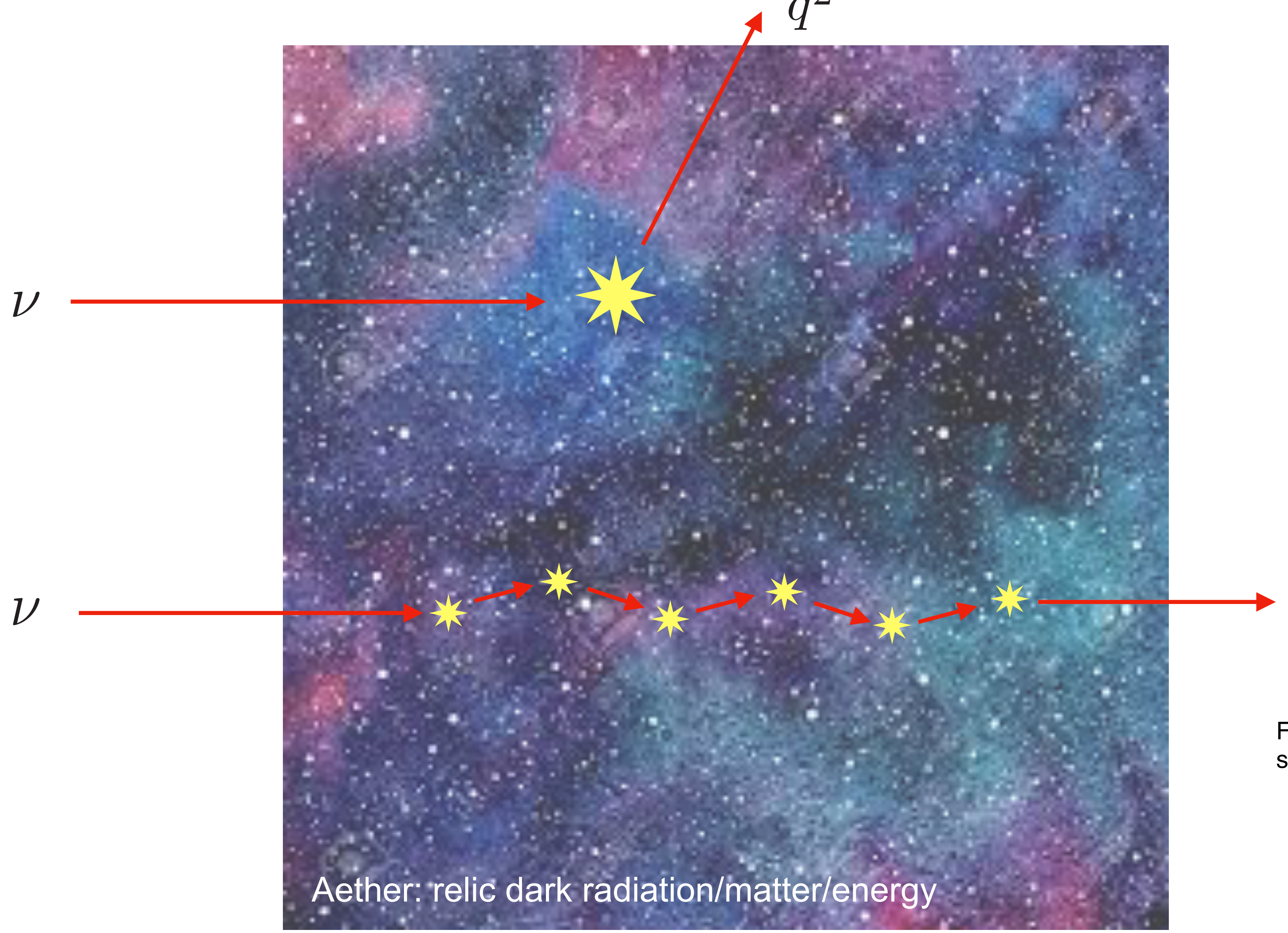
$$\Longrightarrow \quad T_\phi \ll \frac{\rm MeV}{y_s^{1/2}}$$

To be on the safe side:
Better have a late transition!

Light & Weakly-Coupled Dark Sectors: New Signatures in Neutrino Experiments

Light dark sectors coupled via the neutrino portal generically have relic particles…

$$\sim \frac{y_s^2}{q^2}\theta^2$$

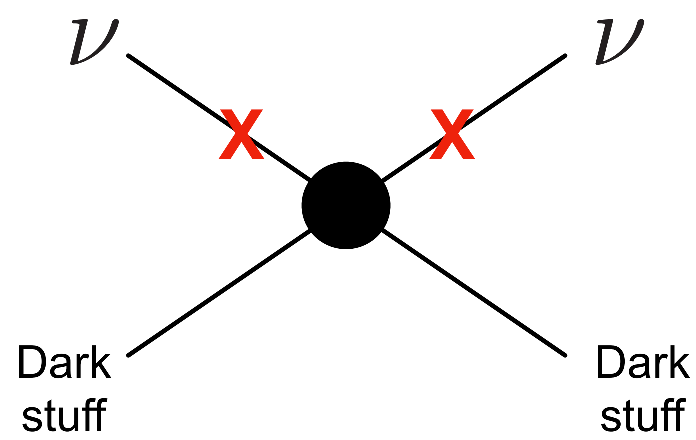


$$\sim \frac{y_s^2}{m_s^2}\theta^2 N_{\rm Dark}$$

For realistic Dark densities neutrinos see a continuous background…

Flavor-dependent (mixing) refractive index: sensitivity to **light, weakly-coupled dark sectors**

Steriles as **mediators** of neutrino-Dark interactions in oscillation experiments:



Unknown

Radiation
or Matter

$$V_{\rm Dark} \sim \frac{g^2_{\rm Dark}}{m^2_{\rm Dark}} \theta^2 n_{\rm Dark}$$

Unknown

A light, weakly-coupled sector
can have a sizable effect!

Steriles as **mediators** of neutrino-Dark interactions in oscillation experiments:

$$V_{\rm Dark} \sim \frac{y_s^2}{m_s^2}\theta^2 n_{\rm Dark}$$
$$\sim \frac{y_s^2}{m_\nu^2} n_{\rm Dark} \sim 10^{-24}\ {\rm GeV}\ \left(\frac{y_s}{10^{-2}}\right)^2 \frac{n_{\rm Dark}}{1/{\rm cm}^3}$$

Coupling to dark radiation

$$\theta \sim \frac{m_s}{m_\nu} \ll 1$$

$$V_{\rm Dark} \sim \frac{y_s^2}{m_s^2}\theta^2 n_{\rm Dark}$$
$$\sim \frac{y_s^2}{m_\nu^2}\frac{\rho_{\rm Dark}}{m_{\rm DM}} \sim 10^{-24}\ {\rm GeV}\ \left(\frac{y_s}{10^{-5}}\right)^2 \frac{1\ {\rm keV}}{m_{\rm DM}}$$

Coupling to dark matter

$$\theta \sim \frac{m_s}{m_\nu} \ll 1$$

$$V_{\rm Dark} \sim g_V \langle V \rangle \theta^2 \sim g_V \sqrt{\frac{\rho_{\rm Dark}}{m_V^2}}\theta^2$$
$$\sim 10^{-24}\ {\rm GeV}\ \left(\frac{g_V}{10^{-18}}\right)\left(\frac{\rm eV}{m_s}\right)^2 \left(\frac{10^{-6}\ {\rm eV}}{m_V}\right)$$

Coupling to very light dark matter (<<eV)

Graham's et al. (2015)

To ensure V remains decoupled:

$$g_V < 10^{-12}\left(\frac{m_s}{\rm eV}\right)^{3/2}$$

F. Capozzi, I. M. Shoemaker, LV

Neutrino oscillations in dark backgrounds…

neutrino/neutrino (anti-neutrino/anti-neutrino) oscillations

$$\mathcal{L} = N_\alpha^\dagger \bar{\sigma}^\mu [i\partial_\mu \delta_{\alpha\beta} + (V_\mu)_{\alpha\beta}] N_\beta + \left\{ \frac{1}{2} N_\alpha^\dagger \left[m_{\alpha\beta} + (F_{\mu\nu})_{\alpha\beta} \bar{\sigma}^{\mu\nu} \right] i\sigma_2 N_\beta^* + \mathrm{hc} \right\}$$

Indistinguishable from a mass…

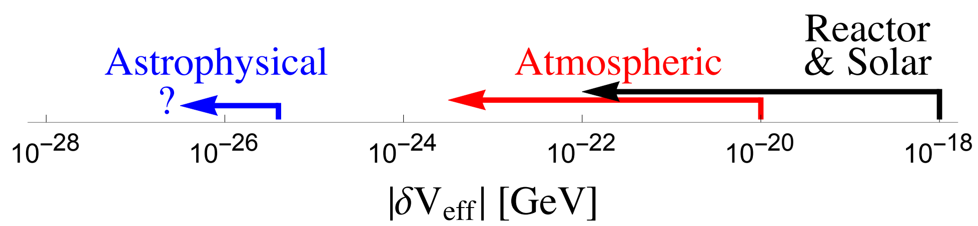
neutrino/anti-neutrino Oscillations

Effective "Hamiltonian"

$$H_{\rm eff} = \left.\begin{pmatrix} |\mathbf{p}| + \frac{mm^*}{2|\mathbf{p}|} - \frac{p^\mu V_\mu}{|\mathbf{p}|} & \frac{4\sqrt{2}}{|\mathbf{p}|} p^\mu (F_{\mu\nu}) \epsilon^\nu \\ \frac{4\sqrt{2}}{|\mathbf{p}|} p^\mu (F_{\mu\nu})^\dagger (\epsilon^\nu)^* & |\mathbf{p}| + \frac{m^* m}{2|\mathbf{p}|} + \frac{p^\mu V_\mu^*}{|\mathbf{p}|} \end{pmatrix}\right|_{p_0 = |\mathbf{p}|} = H_{\rm SM} + V_{\rm Dark}$$

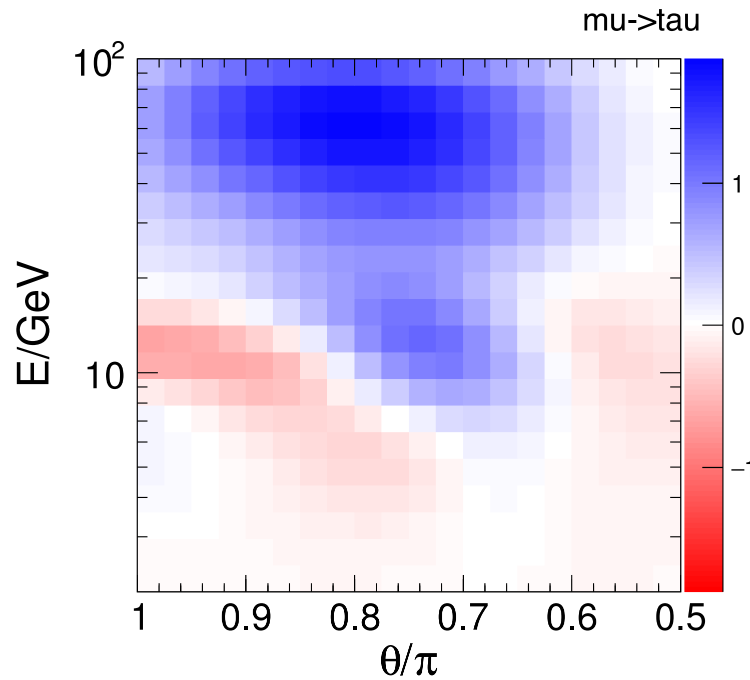
- Large E is good → V,F become more important than the standard effect (mass)
- But not "too large" → **If V,F dominate we loose info on the overall size of V_Dark** (and hence the dark energy scale)**!**

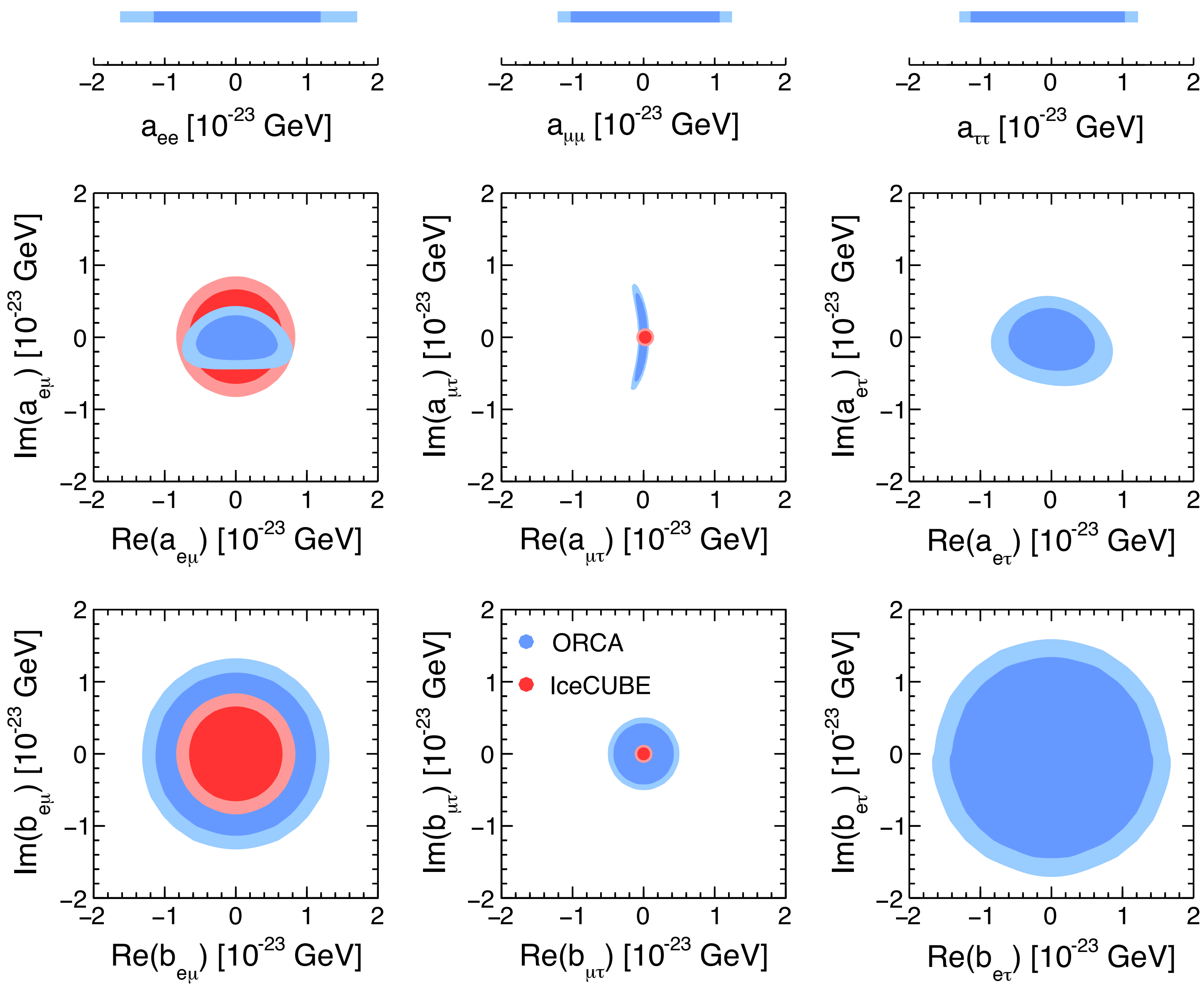
$V_{\rm Dark} \propto G_{\rm Dark} n_{\rm Dark}$ or $\sqrt{G_{\rm Dark} \rho_{\rm Dark}}$



Atmospheric neutrinos

ORCA (KM3NeT project)+IceCube



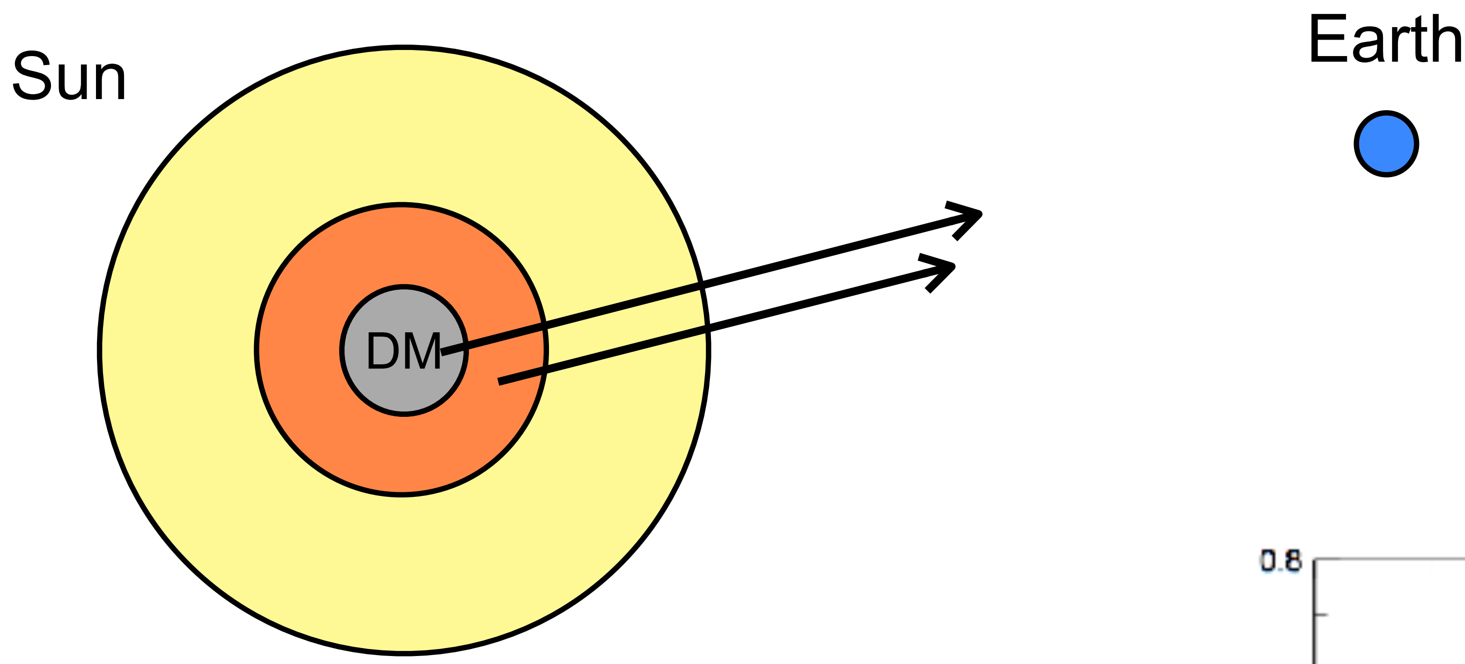


$$a(\hat{\mathbf{p}}) = -V_0 + \hat{\mathbf{p}} \cdot \mathbf{V}$$

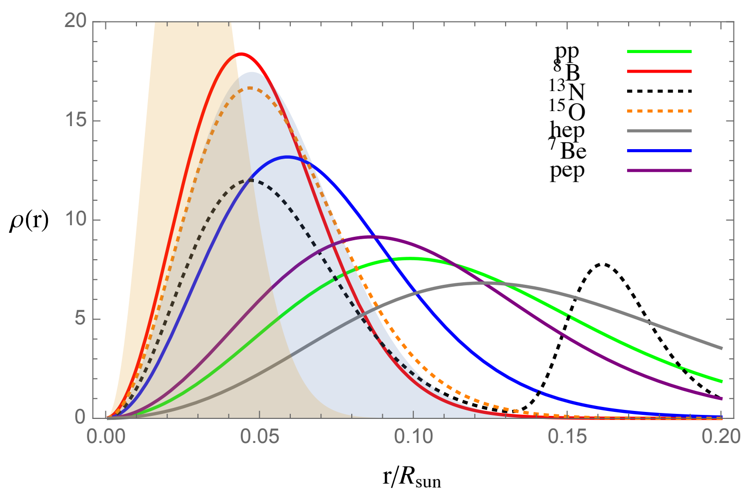
$$b(\hat{\mathbf{p}}) = -4\sqrt{2}(\mathbf{E} + i\mathbf{B}) \cdot \vec{\epsilon}(\hat{\mathbf{p}})$$

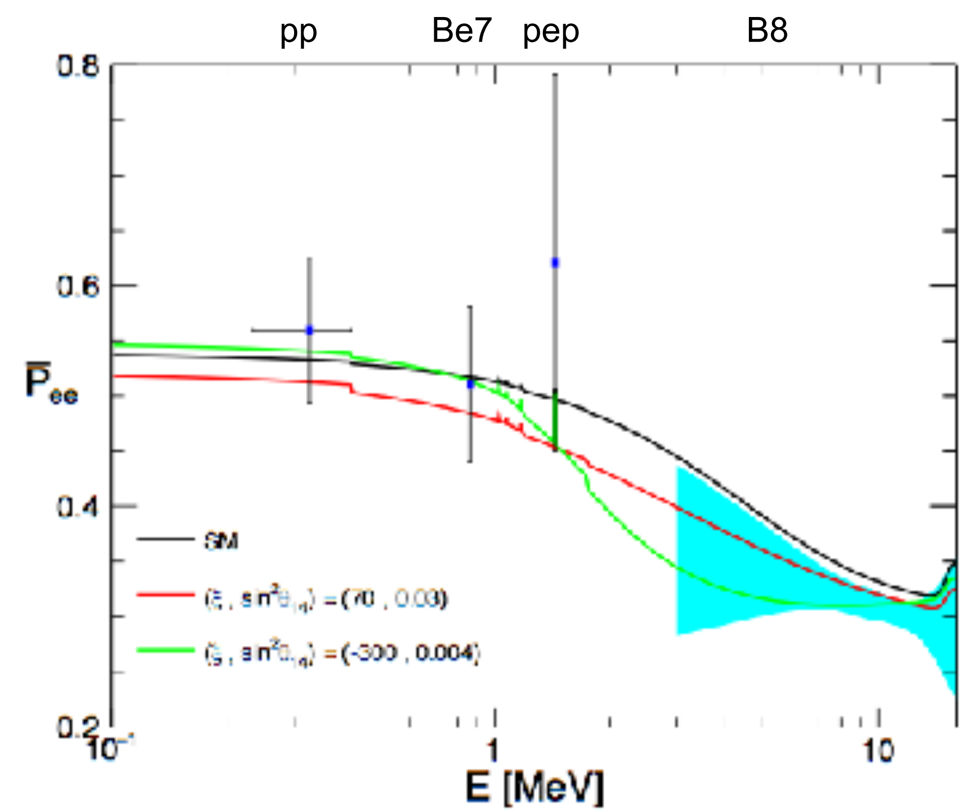
$$V_{\rm Dark} \sim a, b \sim 10^{-24}\ \text{GeV!}$$

Atmospheric neutrinos (ONLY if some dark matter is captured…)



B8 & CNO neutrinos are affected
pp neutrinos only mildly

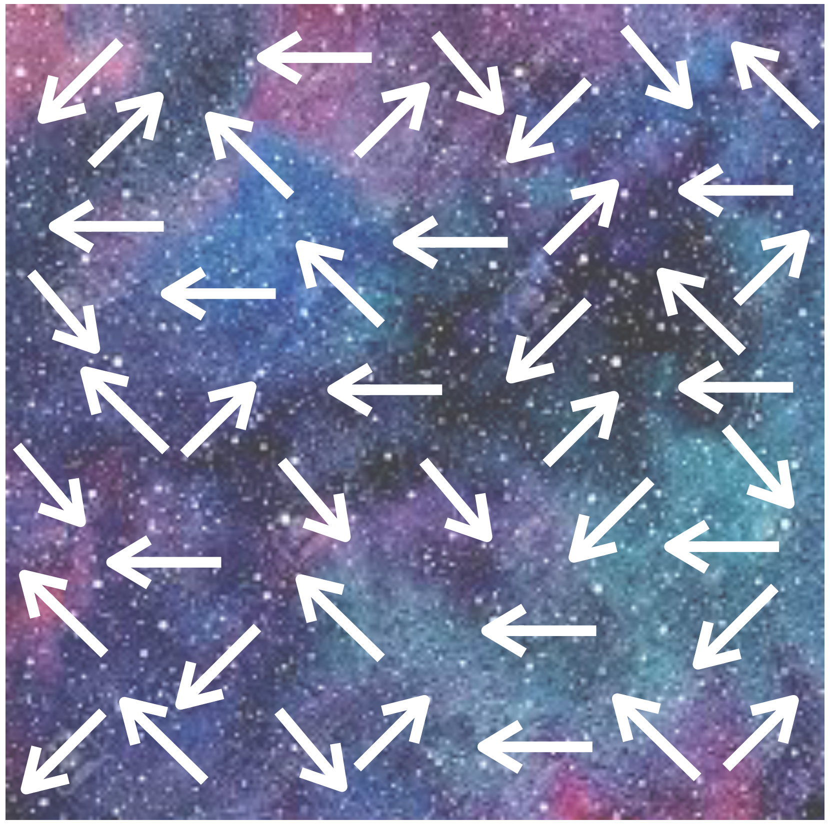




$$\xi \equiv \frac{G_{\rm DM} n_{\rm DM}(0)}{\sqrt{2} G_F n_e(0)}$$

Dark backgrounds or Neutrino Masses? $L^\dagger \bar{\sigma}^\mu L V_\mu$

Dark radiation/matter/energy



Random orientation in small domains:
Rotation invariance preserved on intermediate scales (magnets).

$$\langle E(\mathbf{p})\rangle = \begin{cases} |\mathbf{p}| + \frac{1}{3|\mathbf{p}|}\langle \mathbf{V}^2\rangle + \cdots & |\mathbf{p}| \gg |\mathbf{V}| \\ |\mathbf{V}| + \frac{1}{3|\mathbf{V}|}\mathbf{p}^2 + \cdots & |\mathbf{p}| \ll |\mathbf{V}|, \end{cases}$$

No EW symmetry breaking needed to explain oscillations…

$$\rho_{\rm DE} \sim \langle \mathbf{V}^4\rangle \sim m_\nu^4$$

Dark energy?

Conclusions

- **Exotic light sectors?**
  - Not so crazy… dark matter is weakly-coupled to us and may be very light
  - They may interact with us via the neutrino portal → Cosmology, Astrophysics and Neutrino physics

- **Cosmology and Sterile Sectors:**
  - We do not know the “dark dynamics” → Cosmology cannot robustly exclude dark sectors
  - A dark phase transition below T=MeV implies a standard Neff at BBN and after
  - CMB physics may be affected by ms>eV (eV steriles not easily allowed)
  - Scenarios with a late phase transition, small couplings, ms<eV → standard Cosmology

- **Neutrino portal: ~~Cosmology~~, ~~Astrophysics~~ and Neutrino physics:**
  - Steriles can act as mediators of interactions with light relic dark particles
  - Smoking gun at neutrino experiments: exotic matter potentials (in the cosmo, in the sun, etc.)
  - Can couplings to dark sectors explain the proximity of dark energy and neutrino masses?

Thank You